# Room-temperature operation of a transistor vertical-cavity surface-emitting laser

X. Yu, Y. Xiang, J. Berggren, T. Zabel, M. Hammar, N. Akram, W. Shi and L. Chrostowski

We demonstrate the first room-temperature operation of a transistor vertical-cavity surface-emitting laser (T-VCSEL). Fabricated using an epitaxial regrowth process, the T-VCSEL is electrically a Pnp-type bipolar junction transistor and consists of an undoped AlGaAs/GaAs bottom DBR, an InGaAs triple-quantum-well (TQW) active layer, an Si/SiO$_2$ dielectric top DBR, and an intracavity contacting scheme with three electrical terminals. The output power is controlled by the base current in combination with the emitter-collector voltage, showing a voltage-controlled operation mode. A low threshold base-current of 0.8 mA and an output power of 1.8 mW have been obtained at room temperature. Continuous-wave operation was performed up to 50°C .

Introduction: Transistor lasers have received significant attention during recent years. Based on the monolithic integration of a heterojunction bipolar transistor (HBT) in a semiconductor laser they provide a number of unique properties as compared to conventional diode lasers [1, 2]. A particularly attractive feature is the potential for increased laser modulation bandwidth due to the altered charge dynamics in the base region [3]. Given the growing demand for broadband capacity in optical communication networks this may find important applications. Single-channel data rates of 40 Gbit/s and beyond are e.g. presently considered for local area networks and interconnects. Due to the tough requirements on cost- and power-efficiency, vertical-cavity surface-emitting lasers (VCSELs) are the preferred light-sources for these applications. Whereas VCSELs have been demonstrated with 3dB-bandwidth of 28 GHz [4] and VCSEL-based optical links with modulation speeds up to 55 Gbit/s [5], this is approaching fundamental limits. To reach such high and even higher modulation rates over an extended temperature range and with sufficient output power, radically new design concepts are required. Transistor-VCSELs (T-VCSELs) and their potential for high-speed modulation were evaluated numerically by Shi et al. [6], and very recently the first experimental demonstration of a T-VCSEL at low temperature was reported [7], including the voltage controlled operation of such lasers [8].

In the present work, we have fabricated and investigated a GaAs-based Pnp-type 980-nm T-VCSEL. Continuous-wave operation is demonstrated up to 50°C with a room-temperature (RT) output power of 1.8 mW for a 10·10-µm^2 device, controlled by the base current in combination with the collector-emitter voltage. To the best of our knowledge, this is the first demonstration of the room-temperature operation of a T-VCSEL.
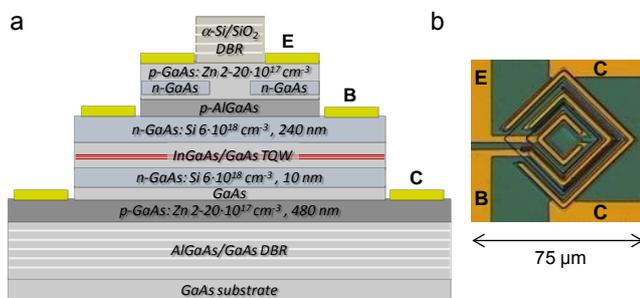

Fig. 1 *T-VCSEL design and layout*
a Schematic cross-section of the T-VCSEL. The emitter and sub-collector regions are modulation doped for minimized optical loss. The emitter (E), base (B) and collector (C) contacts are indicated.
*b* Top-view optical micrograph of a fabricated T-VCSEL.

Device design and fabrication: A schematic drawing of the T-VCSEL is shown in Fig. 1. First, the bottom 35.5 pair Al$_{0.88}$Ga$_{0.12}$As/GaAs Distributed Bragg Reflector (DBR), the collector, base and emitter regions are grown using metal-organic vapour phase epitaxy. Embedded in the base region is an InGaAs/GaAs triple quantum-well (TQW) active layer with photoluminescence wavelength of 965 nm. A square-shaped mesa is etched through the emitter, thereby defining the active region, and an n-type GaAs layer is regrown around the mesa for electrical confinement. Then the whole structure is overgrown by a p-type GaAs layer that completes the emitter region and the five-lambda thick cavity. Larger mesas are etched to access the n-type base region and the p-type sub-collector. Finally, a high contrast, low loss dielectric DBR made out of three pairs of alternating layers of SiO$_2$ and α-Si is deposited on the cavity region. The laser structure is similar to our previous 1300-nm VCSEL design with the details given in Ref. 9.

Device evaluation: Figure 2 shows the measured optical output power (P_{out}) as function of the base current (I_B) for different collector-emitter voltages (V_{CE}). For low values of V_{CE}, P_{out} and the differential slope efficiency increases while the threshold current decreases with increasing V_{CE}, reflecting the gradually increased revere-bias voltage on the base-collector (BC) junction. For higher values of V_{CE}, P_{out} saturates and starts to decrease due to thermal roll-over caused by self-heating. The threshold base current for $V_{CE} > 1$ V is around 0.8 mA. The optical spectra are taken just below and slightly above the threshold current. The measured linewidth of the leading mode is ~0.1 nm, limited by the resolution of the optical spectrum analyzer.
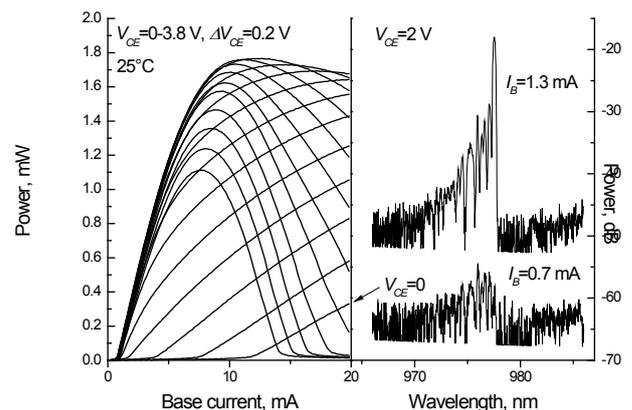

Fig. 2 *Room-temperature light-current characteristics and optical spectra for a 10·10-µm^2 device. The two spectra have been vertically displaced for clarity*
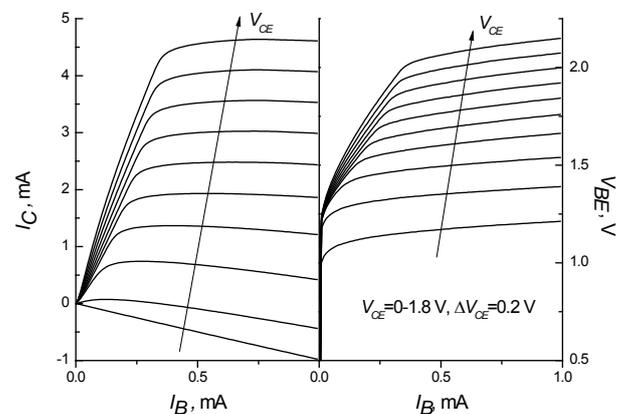
Fig. 3 *I_C and V_{BE} as function of I_B for different V_{CE} as indicated.*

Figure 3 shows I_C and V_{BE} as function of I_B for different values of V_{CE}. For $V_{CE}=0$, I_C is negative throughout the range of I_B since both junctions (EB and CB) are forward biased with corresponding hole injection into the base. For $V_{CE}>0$, I_C initially increases with increasing I_B but then saturates and starts to gradually decrease. Considering the detailed geometry and the biasing configuration of the device, this behaviour is attributed to a gradual turn-on of the CB junction, starting from the edge close to the collector contact and progressing towards the centre region with increasing I_B. The current injected close to the collector contact will not contribute to the lasing modes since it is only pumping the peripheral part of the active region outside the optical cavity. Beyond the kinks in the I_C-versus-I_B characteristics, I_C is composed of two parts; a reverse current at the central part of the device and a forward current in the peripheral region that adds to the rapidly increasing I_B, eventually summing up to $I_C < 0$. In the central region, holes injected from the emitter and electrons diffusing from the base contact provide the optical gain.

Figure 4 shows temperature-dependent current as well as voltage-controlled operation of the T-VCSEL. The high-temperature performance can even further be improved by increasing the spectral offset between the active layer gain maximum (λ_g) and the cavity resonance (λ_{cav}). The minimum in threshold current occurs at around 10°C, corresponding to a slight negative tuning at RT ($\lambda_g - \lambda_{cav} \approx -15$ nm). For the voltage-controlled operation, I_B is set to 8 mA while P_{out} versus V_{CE} are recorded at different temperatures. Similar to the current-controlled operation, a pronounced lasing threshold is observed and P_{out} is limited by self heating and thermal roll-over at high voltages. This voltage-controlled operation is unique to transistor lasers and may find important applications [6].
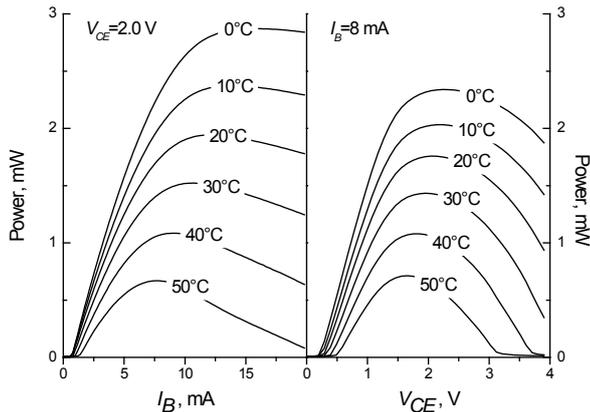
Fig. 4 *Temperature-dependent operation of T-VCSEL using I_B or V_{CE} as control signals.*

Conclusion: The three-terminal operation of a T-VCSEL has been demonstrated. The results indicate that T-VCSELs can reach static performance levels similar to those of conventional VCSELs in terms of output power, threshold current and high-temperature operation.

X. Yu, Y. Xiang, J. Berggren, T. Zabel and M. Hammar (*KTH Royal Institute of Technology, School of Information and Communication Technology, Electrum 229, S-164 40 Kista, Sweden*)

E-mail: hammar@kth.se

N. Akram (*University of VestFold, N-3103 Tønsberg, Norway*)

W. Shi and L. Chrostowski (*Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, BC, Canada*)

References

1 Holonyak, N. and Feng, M.: "The transistor laser", *IEEE Spectrum*, 2006, **43** (2), pp. 50–55

2 Feng, M., Holonyak, N., Walter, G., and Chan, R.: 'Room temperature continuous wave operation of a heterojunction bipolar transistor laser', *Appl. Phys. Lett.*, 2005, **87**, pp. 131103-1–131103-3

3 Tan, F., Bambery, R., Feng, M., and Holonyak, N.: 'Transistor laser with simultaneous electrical and optical output at 20 and 40 Gb/s data rate modulation', *Appl. Phys. Lett.*, 2011, **99**, pp. 061105-1–061105-3

4 Westbergh, P., Safaisini, R., Haglund, E., Kögel, B., Gustavsson, J.S., Larsson, A., Geen, M., Lawrence, R., and Joel, A.: 'High-speed 850 nm VCSELs with 28 GHz modulation bandwidth operating error-freeup to 44 Gbit/s', Electeron. Lett. 2012, **48** (18), pp. 1145-7

5 Kuchta, D.M, Rylakov, A.V., Schow, C.L., Proesel, J.E., Baks, C., Kocot, C., Graham, L., Johnson, R., Landry, G., Shaw, E., MacInnes, A., and Tatum, J: 'A 55Gb/s directly modulated 850nm VCSEL-based Optical Link', IEEE Photonics Conf. 2012 (IPC 2012), Post Deadline paper 1.5

6 Shi, W., Faraji, B., Greenberg, M., Berggren, J., Xiang, Y., Hammar, M., Lestrade, M, Li, Z.-Q., Li, Z.M.S., and Chrostowski, L.: 'Design and modeling of a transistor vertical-cavity surface-emitting laser', *Optical Quantum Electronics*, 2011, **42** (11), pp. 659–666

7 Wu, M.-K., Feng, M, and Holonyak, N.: 'Surface emission vertical cavity transoster laser', *IEEE Photonics Technol. Lett.*, 2012, **25** (15), pp. 1346–1348

8 Wu, M.-K., Feng, M, and Holonyak, N.: 'Voltage modulation of a vertical cavity surface emitting laser via intra-cavity photon-assisted tunneling', *Appl. Phys. Lett.*, 2012, **101**, pp. 081102-1–081102-3

9 Marcks von Würtemberg, R., Yu, X., Berggren, J., and Hammar, M.: 'Performance optimization of epitaxially regrown 1.3-μm VCSELs', *IET Optoelectronics,* 2009, **3** (2), pp. 112–121